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This document describes to the system developers and to the offerors on developmental programs the general insights and the key issues for nuclear survivability at tactical threat levels. Among the topics that are discussed are the nuclear environments and the nuclear survivability criteria. These are followed by a discussion of the possible effects of these environments on the equipment. Effective methods for resolving

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system vulnerabilities and the impact of these methods on the system acquisition cycle also are considered.

The thesis of this document is that nuclear survivability at tactical levels is achievable with an acceptable impact on life cycle cost, program schedule, and system performance parameters. Early implementation and application of nuclear survivability criteria with appropriate documentation, informed trade-off decisions, and management awareness and control will provide the basis for achieving this goal.

Block 7 (Cont'd). Ennis Quigley
Morris Campi

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FOREWORD

This document describes the general insights and the key issues for the nuclear survivability of tactical systems. Volume II deals strictly with the events in a system's life cycle that impact the attainment and the maintenance of nuclear survivability.

This document is an outgrowth of a paper drafted in January 1977, having been distributed in preliminary form as Guideline for Nuclear Weapon Effects Survivability of Tactical Nuclear Systems by Joseph J. Halpin et al, HDL-PRL-76-2 (March 1976). Some of the inputs for this original draft came from Robert Raley and William Taylor of the Ballistic Research Laboratories, Aberdeen, MD, and Werner Stark and John Sweton of the Harry Diamond Laboratories (HDL) It was realized that, although the original draft was intended for a specific system with some additional work, the document could be broadened in scope. At that point, the contributors named in this document performed the necessary modifications and additions. The surgery that was performed was extensive.

In addition to the inspiration provided by the original contributors, there was also the guidance provided by the HDL Nuclear Weapons Effects Program Office. The patience and the intensive reviews performed by Fred Balicki, James Gaul, and John Corrigan are especially appreciated.

The following also are acknowledged for their reviews of and meaningful comments on one of the final drafts: Heinz Mueller, Frank Wimenitz, Paul Trimmer, Harvey Eisen, Roland Polimadei, Daniel Spohn, Ronald Bostak, Robert Pfeffer, and Stewart Share of HDL; Donald Vincent of the National Security Agency; Forest Thompson of the Army Nuclear and Chemical Agency; and Cary Fishman of the Office of the Project Manager, SINCGARS.

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1. INTRODUCTION

The more recent emphasis[1] and interest in developing military equipment that will survive in a theater or tactical nuclear engagement has brought increasing attention to the management and the execution of such development programs. In the past, most of the Department of Defense (DoD) nuclear survivability technology was oriented to strategic systems. For these strategic systems, nuclear survivability is a must. Moreover, the environments that these systems must survive are generally far more severe than the environments that tactical systems* must survive. The reason for this difference in the environment levels is the intimate association of man with most equipment in the tactical nuclear war. Recognizing the lack of appropriate and current overview documentation to support nuclear survivability for the tactical system, we here document the most current insights based on our research and experiences over the years. Volume II deals strictly with the system acquisition aspects of nuclear survivability.[2]

The specific objective of this document is to describe to the system developers and to the bidders on developmental programs the general insights and the key issues for nuclear survivability. Among the topics discussed are the nuclear environments and the rationale for the nuclear survivability criteria. These are followed by a discussion of the possible effects of these environments on the equipment. Effective methods for resolving system vulnerabilities and impacts of such programs on the system acquisition cycle also are considered.

This document is not intended to be a recipe book on how to satisfy the system's nuclear survivability requirements. No document of this size could do that. Our emphasis has been to present the most current insights and, at the same time, to present as much of the total picture as possible. Additional guidance is available through the mentioned expertise of various Government and industry sources, the cited data sources, and the Selected Bibliography. Support of the nuclear survivability concepts also is available through Army Regulation AR 70-60, Army Nuclear Survivability.[3] The impacts of this regulation are discussed.

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[1]*The Theater Nuclear Force Posture in Europe, A Report to the United States Congress, Office of the Secretary of Defense (1975).*

[2]*Joseph J. Halpin and John P. Swirczynski, Nuclear Weapons Effects on Army Tactical Systems, Vol. II, Management, Harry Diamond Laboratories HDL-TR-1882-2 (May 1979).*

[3]*Army Nuclear Survivability, Department of the Army AR 70-60 (20 September 1977).*

**In this paper, "tactical" refers to those systems used in theater nuclear warfare.*

The thesis of this document is that nuclear survivability is achievable with an acceptable impact on life cycle cost, program schedule, and system performance parameters. Early implementation and application of nuclear survivability criteria with appropriate documentation, informed trade-off decisions, and management awareness and control will provide the basis for achieving this goal. The nuclear survivability goals can be met in more ways than one, each with its advantages and disadvantages. However, prudent decisions can be made only by informed personnel. The justification of this thesis lies within this document.

2. NUCLEAR WEAPONS EFFECTS PHENOMENOLOGY

2.1 Nuclear Environment

The nuclear environment comprises several components created by the detonation of a nuclear (fission) or thermonuclear (fission-fusion) weapon. The direct weapon output components are neutrons, electrons, fission fragments, bomb debris, alpha particles, gamma rays, and x rays. The indirect weapon effects are electromagnetic pulse (EMP), thermal radiation, and the blast or pressure wave. These indirect effects are caused primarily by the weapon's gamma- and x-ray interaction with the atmosphere. In addition to the indirect weapon effects, an energy-modified spectrum of neutrons and a time-modified pulse of gamma rays arrive at the tactical system.

These environmental components do not arrive simultaneously at the system. Table 1 lists the arrival time and the pulse widths of the constituents of the nuclear environment for a 40-kT near-surface burst at a range of 1300 m. For instance, gamma rays travel at the speed of light. Neutrons travel at slower speeds, depending upon their individual energies, and, therefore, they begin arriving after the initial or prompt gamma pulse. This pulse of neutrons broadens with distance. Interactions of the neutrons with the air and ground molecules produce neutrons of lower energy and additional gamma rays. These indirect gamma rays are referred to as delayed gammas. The EMP is created by the atmospheric ionization, which is caused by the prompt gamma, x, and delayed gamma rays. Being an electromagnetic wave, EMP travels at the speed of light. Its arrival time is nearly simultaneous with the arrival of the gamma ray. Thermal radiation from the weapon's fireball also is electromagnetic radiation traveling at the speed of light. This radiation results from the excitation and the radiative decay of air molecules. A blast or a shock wave is created by the expansion of the very hot, high pressure gases in the fireball. Because the blast wave transport is dependent on air molecule motion, the time of arrival of the blast wave is much later than the electromagnetic phenomenon.

TABLE 1. PULSES PRODUCED AT 1300 m FROM 40-kT WEAPON (NEAR SURFACE)

Type of pulse	Time of arrival of pulse maximum (s)	Pulse width (s)	Remarks
Prompt gamma	$\sim 5 \times 10^{-6}$	$\sim 3 \times 10^{-2}$	High dose rate, low dose
Electromagnetic	$\sim 5 \times 10^{-6}$	$\sim 10^{-3}$	-
Neutron and delayed gamma radiation	$\sim 5 \times 10^{-5}$	$\sim 10^{-3}$ (50% of dose) ~ 10 (90% of dose)	Low dose rate, high dose
Thermal	~ 0.2	~ 2	$\sim 80\%$ of energy content
Blast	2	1	-

One result of the nonsimultaneity of nuclear effects is that the effect of the total environment can be greater than the sum of the effects from the individual environmental components. For example, the potential for material failure due to blast is greatly enhanced if the target material is already weakened by the preceding thermal pulse. Another example is the synergism between gamma-ray effects and EMP effects (sect. 2.3.3.1).

Another consequence of the weapon output is the radioactivity induced in the weapon system's materials and in the soil. This radioactive debris is lifted and spread over a wide region. Some of this radioactive debris may remain quite mobile in debris clouds, which can be deposited in rain (rainout) or onto the surface of the earth by gravity or wind (fallout). This rainout or fallout poses a long-term threat over wide areas. Although this threat is an important consideration as a biological threat, because of the low total ionizing dose there are no significant consequences of this radiation to the equipment response.

The discussions of the nuclear environment up to this point pertain to a tactical, low-altitude, nuclear burst. There have been postulated and accepted scenarios in which large yield weapons could be detonated at high altitudes (>30 km). Although the slant ranges for these bursts preclude the blast, thermal, and initial radiation (neutrons and gamma rays) from reaching the surface of the earth in significant intensity, an intensely pulsed electromagnetic field at a target that is on or near the ground can be produced. This high-altitude EMP (HAEMP) is characteristically different from the low-altitude EMP (LAEMP) in amplitude, spectrum, polarization, and planarity. The implications of these factors are discussed in section 2.3.4.1.

The nuclear-induced air ionization is responsible for a secondary phenomenon called blackout. This produces noise or loss of signal for radio wave transmissions. In most tactical situations, this is not a long duration effect, and radar and radio transmissions are near normal within minutes. A notable exception is high-frequency satellite communications networks. In this exception, if the ionization is in the path of the signal, the transmission may be affected for hours.[4, 5]

2.2 System Nuclear Survivability Criteria

Nuclear survivability is the capability of a system to withstand a nuclear environment without suffering a loss of its ability to accomplish its designated mission within an acceptable time span. The decision on whether to require nuclear survivability for a system is based on its possible use in a nuclear conflict, the criticality of its mission in such a conflict, the battlefield density of the equipment, and the timely replacement of the crew and destroyed or damaged equipment. Inputs on these issues are submitted by the U.S. Army Training and Doctrine Command and the U.S. Army Materiel Development and Readiness Command (DARCOM) to the Army Nuclear and Chemical Agency (ANCA), Fort Belvoir, VA, Office of the Deputy Chief of Staff for Operations and Plans. Being the proponent organization for nuclear survivability criteria, ANCA receives inputs and recommends suitable criteria for each system.[6]

Most Army systems are man-machine combinations in which a human operator or a crew is necessary for the system to perform its intended function. The basic philosophy of nuclear survivability of such a man-machine system is that the machine portion of the system should survive if a sufficient percentage of its crew can survive long enough to complete the mission. When the equipment and its operator are subjected to the same environment, the survivability criteria are determined by man's vulnerability, which is modified as appropriate by attenuation or protection factors and selected equipment damage mechanisms. The degree of attenuation depends on the weapon yield variables, the slant range, and atmospheric conditions between the burst and the system. The protection factors result from a modification of the nuclear environment

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[4] *Nuclear Blackout of Tactical Communications, U.S. Army Nuclear and Chemical Agency, Fort Belvoir, VA, Nuclear Note No. 4 (August 1976).*

[5] *J. D. Illgen, Analysis of Typical Theater Army Communication Links in a Nuclear Environment (U), General Electric Co., Philadelphia, PA, HDL-CR-75-016-1 (July 1975). (Defense Documentation Center AD C002803) (SECRET RESTRICTED DATA)*

[6] *Nuclear Survivability Criteria for Army Tactical Equipments (U), U.S. Army Nuclear and Chemical Agency, Fort Belvoir, VA, ACN 04257 (1974). (CONFIDENTIAL RESTRICTED DATA)*

by the vehicle or by an enclosure (such as a building or a signal shelter) surrounding the man-machine system. How the environment can be modified can be demonstrated when the equipment and the man are in an armored vehicle. The enclosure provides protection against thermal radiation, attenuates neutron fluence and gamma radiation, and protects personnel from debris accelerated by the nuclear burst.

Various configurations of the man-machine combination are possible. If the man is protected (such as in a foxhole) and the equipment is exposed, then the survivability criteria for the equipment are based on the protected man's vulnerability. On the other hand, if a man is exposed and his equipment is protected, the survivability criteria for the system are based on the unprotected man's vulnerability.

The goal is nuclear survivability specifications on the equipment, not specifications of man's survivability. To accomplish this goal, man's vulnerability to the various components of the nuclear environment must be integrated with the limiting damage factors on the equipment survivability. Both the personnel casualty-producing mechanisms and the equipment damage factors are functions of weapon yield and slant range. On a graph of range versus yield, one can plot the appropriate isocasualty and isodamage contours associated with each mechanism for the combination of man and equipment under consideration. With all the pertinent contours for a given system on one graph, the contour of the maximum effective range of this combination of effects can be determined. This contour is referred to as the "governing envelope." This envelope (1) defines the range at which personnel will satisfy the operational constraints and (2) determines the range for each yield at which the equipment must survive.

A range of nuclear weapon yields is applied to this governing envelope. This range is dependent on intelligence information and tactical employment considerations and represents the most probable threat-yield spectrum. The highest values of the various nuclear environment parameters on the governing envelope are normally found at the end points of this threat yield spectrum and at the points of slope discontinuity in the governing envelope. System nuclear survivability criteria are established as the worst-case levels of effects compiled from all these points. By this method, there is a balance of all the effects over the yield range of interest. However, the nature of these balanced nuclear survivability criteria is such that these environments cannot exist simultaneously for any one burst situation, that is, one yield and one slant range. Slant ranges on the order of 1 to 2 km are typical survivability ranges for Army tactical equipment.

There are some systems for which the usual man-machine relationships do not apply. These can occur when humans do not comprise part of the system, when most of a system's lifetime is spent in battlefield storage or in a depot, or when a unique man-machine relationship exists.*

Nuclear survivability criteria are established case by case, and, in all cases, the entire stockpile-to-target sequence should be considered when criteria are requested. Many factors directly bear on the percentage of equipments required to survive in a nuclear engagement. Trade-offs among (1) numbers of systems deployed, (2) the research, development, and production impacts of nuclear survivability requirements, and (3) the nuclear survivability criteria should be considered. Both ANCA and the Harry Diamond Laboratories (HDL) Nuclear Weapons Effects Program Office (NWEPO) support and coordinate such trade-off analyses. Regulatory support and guidance are provided[3] by AR 70-60 (sect. 3).

2.3 Nuclear Weapons Effects

In the above discussion, we consider what the weapon output is, how this output is transported to a system, and how system nuclear survivability criteria are determined. The next step is to evaluate how these environments interact with equipment, materials, and components and how one should deal with these interactions. To do this evaluation, the following discussions are divided into four major areas: (1) blast, (2) thermal radiation, (3) initial nuclear radiation, and (4) EMP. The characteristics of the environment, the effects of the environment, system hardening considerations, and system hardening validation are discussed in the following sections.

2.3.1 Nuclear Blast

This section describes what blast is, how it is generated, how the resultant blast wave engulfs and loads a target, by what mechanisms the blast loads result in damage, and what general procedures might reduce or eliminate a target's susceptibility to blast damage.

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[3]*Army Nuclear Survivability, Department of the Army AR 70-60 (20 September 1977).*

**The overwhelming majority of man-machine combinations allows for man to be temporarily incapacitated (combat ineffective). In other applications, such as a pilot, there is no allowance for even short periods of incapacitation. Also, a system may be so critical to force effectiveness that crew replacement is a viable option.*

The effects of a blast wave are commonly thought of as limited to structural damage to tanks, vehicles, and buildings. More recently, there has been documented the significance of other effects such as blast-induced damage to antennas, blast-induced shock and vibration problems in electronics, damage to electronic signal shelters, and the synergism of blast and thermal radiation. Therefore, nuclear blast damage considerations should cover crushing, deforming, jarring of sensitive equipment, tumbling and subsequent impact, overturning, and impact of debris. The common approaches to solving these problems are structural reinforcement, shock isolation, and tie downs. Retrofitting to harden systems to the nuclear blast environment is not only costly, but often not compatible with the form, the fit, and the function requirements of the system. However, materials and approaches are being developed that can make the blast hardening of systems both cost effective and compatible with design requirements.

The service shock environment (handling, transportation, and service use) is characteristically different in both amplitude and frequency from the nuclear blast-induced shock and vibration environment. In most blasts, the nuclear shock and vibration environment is of higher frequency and greater amplitude. Each system must be evaluated for its response to these two very different environments.

2.3.1.1 Blast Environment

The detonation of a nuclear weapon rapidly releases a large amount of energy in the form of x rays. These x rays are rapidly absorbed by the air, heating the air within a limited space. This spatially limited volume of hot compressed gases rapidly expands and pushes a wave of shocked air, a "blast wave," in front of it. This wave is characterized by a sudden increase in pressure at the "blast front," a gradual decrease in pressure to the predetonation (atmospheric) air pressure, a further decrease in pressure below atmospheric pressure due to the overexpansion of the hot compressed gases, and an eventual return to the atmospheric pressure. Figure 1 shows in general the variation of pressure with time at a fixed location as the wave passes that location. The blast wave generated by the detonation expands radially from the point of origin.

The sudden increase in pressure at the blast front is accompanied by an increase in density and temperature and causes an outward airflow. The airflow behind the blast front is known as the "dynamic overpressure" and is a wind gust.

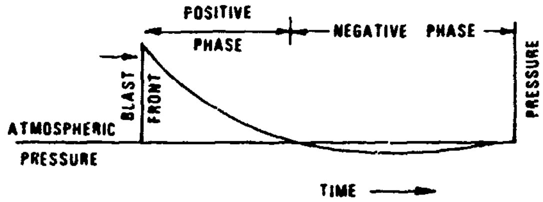

Figure 1. Variation of pressure as wave passes location.

As the blast wave passes a given point in space, the pressure, the temperature, and the density rise rapidly from ambient to levels that are dependent upon the detonation yield and the distance (range) from the burst point. After this rise, the air behind the blast front flows rapidly from the origin. The pressure, the temperature, the density, and the rate of airflow then gradually decrease until the predetonation conditions are resumed. This overpressure portion of the blast wave is called the positive phase. The peak overpressure in this phase is denoted as the positive overpressure, the peak static overpressure, or simply the peak overpressure. The length of this positive phase, that is, the length of time required for this phase to pass a given point, is called the positive phase duration.

While the blast wave expands outward, hot, compressed gases cool and cause a reduced pressure near the origin and, consequently, a flow of air back toward the origin. The overexpansion and the resultant reverse flow cause the local pressure to fall below and then slowly return to atmospheric pressure. This portion of the blast wave is referred to as the "negative phase" and is characterized by a pressure, a temperature, and a density that are lower than the predetonation atmospheric conditions and an airflow (wind gust) toward the detonation origin.

To illustrate the magnitude of some of the parameters described above, let us look at some examples of blast waves generated by the detonation of a 20-kT nuclear weapon (equivalent to 20,000 tons of TNT) detonated at the ground surface.

Peak overpressure (kPa)	103.4	34.5	6.9
(psi)	15.0	5.0	1.0
Time from detonation to blast wave arrival (s)	0.8	2.0	7.8
Ground range (km)	0.64	1.28	3.20
Maximum flow velocity (m/s)	172	69	17
Equivalent wind speed (km/hr)	616	248	59.2
Positive phase duration (s)	0.6	0.8	1.6

From these examples, as the blast wave expands away from the point of origin, there is a reduction in the maximum pressure, an increase in the time from detonation to blast wave arrival, a reduction in the maximum flow velocity (wind speed), and an increase in the duration of the wave.

The blast wave parameters are a function of the weapon yield. For some equipment, two sets of blast environments are specified. The primary differences are in the peak overpressure and the positive phase duration of the blast wave. When two sets of criteria are given, the system response and hardening must be evaluated for both sets.

2.3.1.2 Blast Effects

To illustrate how a blast wave interacts with a target, consider a simple rectangular box target resting on the ground (fig. 2). As the blast wave (fig. 2a) encounters the target (fig. 2b), a portion of it strikes the target and reflects, that is, reverses its direction of travel. The reflection significantly increases pressure. For very low pressures, on the order of 6.9 kPa, the reflected pressure is approximately two times the incident blast wave pressure. For higher incident pressures, 103.4 to 138 kPa, the reflected pressure is perhaps three times the incident pressure. For very high pressures, hundreds to thousands of kilopascals, the reflected pressure can be as much as 10 times the incident pressure. As the blast wave continues to engulf the target (fig. 2c, 2d), the undisturbed portion of the blast wave continues, and the reflected pressure that is applied to the target is reduced. Once the undisturbed blast front reaches the rear of the target (fig. 2e), it continues to expand down the back of the target until eventually the target is completely engulfed by the blast wave (fig. 2f).

Two sets of forces or loads act on a target that is subjected to the nuclear blast environment. First, the time-varying, static overpressure tends to crush the target. As noted in figure 2, these overpressures interact over the target in a complex way with their amplitudes varying with time and distance from the target. This crushing phase is referred to as the "diffraction phase" of the blast loading.

By the time that the diffraction phase is complete, the dynamic pressure that causes drag loading (the second set of target loads) becomes an effective damage mechanism. This dynamic pressure tends to translate or overturn the target. The strength of the drag loading on the target depends on the dynamic pressure, the duration of the applied pressure, and the size and the shape of the target. In addition, the blast winds pick up dust, debris, and possibly other small equipment and subjects the target to debris impact or missiling. These can increase the possible damage to the target.

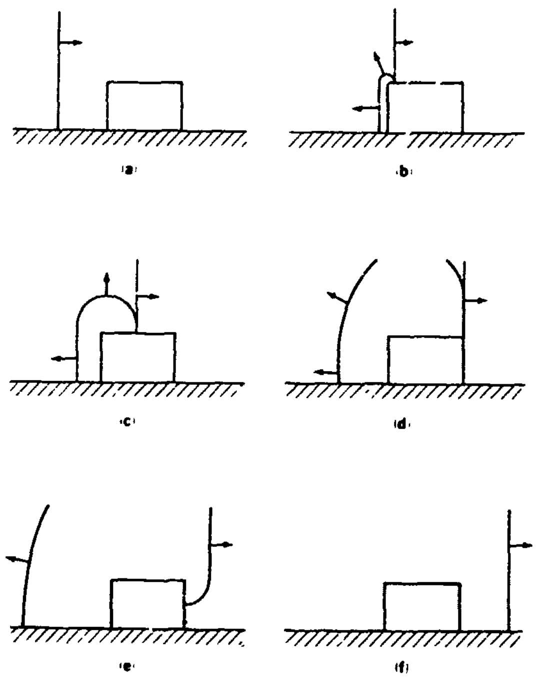

Figure 2. Blast wave engulfing target.

Several types of damage to the target might result from the blast wave impinging on and subsequently loading the target. When the blast front first encounters the leading surface of the target, a slap or a hammer blow is imparted. This slap causes a large, high-frequency shock (acceleration) to be induced in the outer structure of the target and to any internal components that might be in structural contact with the outer container. This acceleration can do considerable damage to various types of internal and external components and mechanisms. For example, fragile, exterior, optical components may be cracked or shattered. As the blast wave engulfment of the target continues, the surfaces can buckle or the structure can be crushed. Buckling can be a damage mechanism when the system or the structure walls come in contact with internal mechanisms, wires, or components.

The diffraction loads are reduced by varying degrees if there are openings in the structure that allow the internal pressure to increase due to pressure leaking into the structure; but this reduction, in turn, subjects the interior to a varying pressure environment. Open tank hatches, electronic shelter doors, or air vents allow for these pressure leaks. Not only do these leaks provide a path for dust and debris, but the equipment inside the enclosure, which was considered to be protected from the blast overpressure, can now be unexpectedly subjected to the incident overpressure.

If the target equipment survives the acceleration to its structure or internal components and the crushing effects of the blast wave engulfment, it is subject to the influence of the drag loading. Drag loading attempts to rip off exterior components and translate the equipment as a whole. When the friction between the ground and the equipment is high, the equipment may overturn. Otherwise, it may be translated or accelerated to some velocity, which depends upon the equipment's size and weight, and may consequently impact some other object, another system, or a terrain feature such as a rock, a hill, or a tree. The primary drag loading damage mechanism on a small object, such as a radio, is solid impact. However, with a large object, such as a truck, the drag loading will most likely produce overturning. For higher yield weapons, the duration of the dynamic pressure is longer, the magnitude is larger, and, therefore, there is a greater potential for overturning and translational damage.

Concurrent with the loading, the target is subjected to the debris carried along in the blast wave. When small particulate material such as dust, sand, or vegetation impinges on the target, a scouring or sandblast can occur, which causes damage, particularly to optical systems. Also to be considered is the penetration of particulates into the system through vents, openings, tears, rips that might have resulted from the crushing or buckling of the structure, or holes caused by the penetration of large pieces of debris. This particulate matter that may have entered the system is capable of damaging the sensitive components of many systems. Larger debris fragments from other targets, tree limbs, or rocks may actually penetrate the structure.

Blast damage is a function of weapon yield, the terrain involved, system orientation, and the way that the target interacts with and then reacts to the blast wave. System response analysis, therefore, is complex. Figure 3 shows some experimental threshold values for four classes of military equipment.

2.3.1.3 Blast Hardening Approaches

Once the blast environment has been specified, the types and the phases of loading have been determined, and the resulting damage mechanisms have been identified, various methods that might be employed to lessen or eliminate damage to the target must be considered. Shock-induced acceleration may be reduced or eliminated by employing shock isolation devices and by providing rattle space. For shock isolation, internal components are not placed in contact with the container, but are shock mounted so that the total, slap-generated acceleration is not transmitted to the internal components. Rattle space is provided so that the outer container can be deformed without contacting the internal components. Buckling and crushing are overcome by increasing the structural strength of the container.

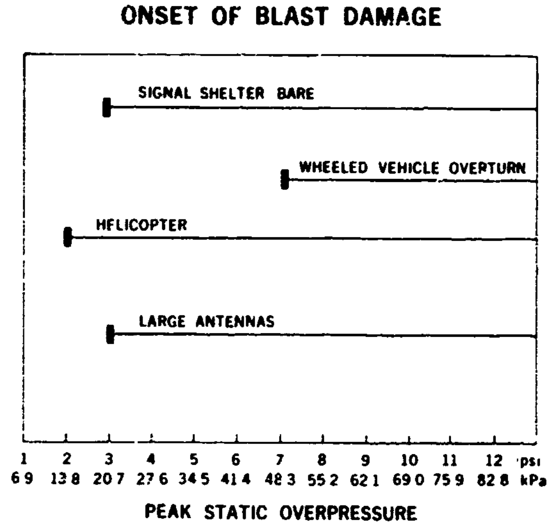

Figure 3. Thresholds for nuclear blast-induced damage in typical classes of Army equipment.

Hardening against debris borne by a blast wave can be accomplished through the use of impact-resistant materials and covers for particularly vulnerable parts. Dust penetration can be prevented through the addition of conventional seals and filters, where adequate consideration is given for nuclear blast and thermal radiation-induced changes in these seals and filters. Fragment penetration can be reduced through the incorporation of armor through the use of either heavier case materials or some of the modern configurations of woven Aramid fiber materials such as Kevlar sandwiches or honeycombs.

Thus far, all of the techniques for hardening have applied to the static overpressure problem. Techniques for hardening against the overturning or translational effects of the drag loading phase, however, must be defined separately for various types of targets. For small portable targets such as hand-carried or backpack radios, tying down the targets might be an acceptable solution. For large targets, such as vehicle-mounted electronic shelters, which must always be able to be mobile, techniques that would increase blast stability include outriggers or tie downs.

2.3.1.4 Blast Survivability Validation

Most systems are complex physically, and, therefore, interactions with a complex blast environment are often quite difficult to model analytically. The use of analytical tools that have been validated by experiment is sufficient to validate blast survivability. Verification of the analytical tools by experiment also is difficult and complex; in rare cases, direct experiments on Army equipment could cost less. In many cases, scale-model experiments have been useful to define the major damage mechanisms and the worst-case orientations. All blast simulators, including high-explosive field tests, have some limitations that preclude testing a system to the complete nuclear threat of interest. Typical limitations are the size of the target that can be tested, the pressure level to which the target can be exposed, the duration of the blast wave that can be generated, and the shape of the pressure-time history that can be imposed on the target. The infrequency, the high costs, the use of only one one shot, and the singular environment of a high-explosive field test simulation are specific limitations of this technique. Therefore, a thorough validation program should consist of analysis and experiments.

For such a combined program, the following steps might be taken:

a. Identify the best existing analytical tool for predicting the structural or whole body response of the target, such as TRUCK.[7]

b. Define the major damage mechanisms and worst-case loading parameters by analysis or scale-model testing.

c. Identify the blast simulator[8] that would most nearly produce the desired loading parameters.

d. Analyze the system response in this blast simulator environment.

e. After designing the system to survive, test the system by using the selected simulator.

f. Compare the analytical and experimental results, evaluate the ability of the analysis to predict the structural response, and modify the analysis if required.

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[7] *Norman P. Hobbs, John P. Walsh, Garabed Zartarian, William N. Lee, and Yau Wu, TRUCK--A Digital Computer Program for Calculating the Response of Army Vehicles to Blast Waves, Kaman Avidyne, Burlington, MA DAAD 05-74-C-0744, KA TR-136 (March 1977). (Defense Documentation Center AD E430051)*

[8] *Blast and Shock Simulation Facilities in the United Kingdom, Canada, and the United States, Rev. ed., Defense Atomic Support Agency DASA 1627 (April 1967). (Defense Documentation Center AD 462107)*

g. Optionally, extend the experimental and analytical comparisons to include the test results of a high-explosive nuclear simulation event, and modify the analysis if required.

h. Use the verified analytical tool to predict the response of the target to the tactical threat criteria.

If all of the proposed steps are sucessfully completed, then it can be assumed that system hardening has been validated for the proposed threat. It can be assumed also that an analytical tool has been verified that could be used to revalidate the system when the threat level changed or to evaluate similar systems to the blast environment. Since all nuclear weapons environment simulators have limitations, this general procedure is recommended for not only the blast environment, but all the constituents of the nuclear environment.

2.3.2 Nuclear Thermal Radiation

The popular concept of the effects of nuclear thermal radiation is often limited to burning and melting of materials. However, there are more subtle effects at low fluences in optical equipment and electronic systems. The precise determination of thermal effects is hampered by inadequate materials data, and, therefore, one approach is to use worst-case calculations to focus attention on the most serious problems. System thermal radiation survivability can sometimes be validated analytically. New simulation techniques are being evaluated to improve the validation of system thermal response.

2.3.2.1 Thermal Effects

The thermal effects produced in materials by a nuclear thermal radiation environment are due to an increase in the materials' temperature. This increase is brought on by the absorption of all or part of the thermal radiation incident on the material. This temperature increase can produce the following: flaming, smoking, ablating, melting, and vaporizing of the material; degradation of the electrical and optical properties of the material; and thermal stresses, displacements, thermal buckling, and degradation of the structural properties of the material. These thermal effects can significantly influence the effects of the subsequent air blast loading and, therefore, must be considered in any blast effects analysis.

Important points about thermal radiation from a nuclear explosion are not only that the amount of energy may be considerable, but also that it is emitted in a very short time. For example, the approximate duration of the thermal environment of a 100-kT weapon is 3 s. Consequently, the energy absorbed by poor heat conductors is largely confined to a shallow depth of the material, and temperatures can be very high at the surface of the material.

Because the magnitude of the thermal effects is highly dependent not only on the materials that make up the system, but also on the geometry of the materials and the thermal environment, available effects data are limited to a specific thermal environment and the system materials exposed to it. Consequently, thermal effects analysis of a system must generally be done system by system for any system's specific thermal environment.

Frequently, rough calculations can be made to determine whether thermal radiation-induced temperature increases are a problem. These calculations should assume a worst case; that is, all the incident energy is absorbed, unless there are data to the contrary. This technique is useful in eliminating those materials or portions of a system that are not a problem. On the other hand, questionable areas are identified for further evaluation. To obtain the greatest accuracy, this latter evaluation is generally experimental.

Effects such as flaming, smoking, ablating, melting, vaporizing, and degradation of electrical, optical, and structural properties can best be analyzed experimentally by using a simulated nuclear thermal environment such as that produced by the solar furnace at the White Sands Missile Range, NM. Loop et al[9] list additional thermal radiation sources. These sources are limited in that only small areas of the materials can be exposed to the thermal environment, and they may not be able to provide the required thermal flux rate. It is because of this limitation that thermal stress, displacement, and buckling effects must be analyzed by using heat transfer and structural response computer programs. This approach is not as straightforward as it seems since these programs require, as input, temperature-dependent material property data that often do not exist. However, for most materials and systems, the thermal constituent of the tactical threat may not cause serious degradation or damage.

Once thermal effects and their magnitude have been determined, it is then necessary to determine to what extent all of these effects degrade the operational function of the system.

2.3.2.2 Thermal-Hardening Techniques and Protective Measures

The extent of the effects produced by the thermal environment in materials depends largely on the temperature increase in the materials. For thermally conducting materials, the temperature

[9]*John D. Loop, David L. Nebert, and Ennis F. Quigley, Characteristics of High Intensity Facilities for Nuclear Thermal Effects Analyses of Tactical Systems, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD, BRL-MR-2083 (December 1970). (Defense Documentation Center AD 880215)*

increase can be minimized by increasing the thickness of the material or reducing the amounts of thermal energy absorbed or both. For thermally nonconducting materials, the temperature increase can be minimized only by reducing the amount of energy absorbed by the material. This amount can be reduced by (1) coating the material with a heat-dissipative material, such as an ablator, or with a highly thermal radiation-reflective material or (2) shielding the material. When shielding, one should consider the thermal radiation as arriving from all directions and not merely on a line of sight from the fireball. Any shield that merely intervenes between the material and the fireball may not be entirely effective.

Optical systems are especially vulnerable to the nuclear thermal environment and, generally, can be protected only by mechanical, electrical, or chemical shutters. Nonconducting or insulating components such as plastic knobs, electric cable insulation, fiber optic cables, rubber grommets, seals, tires, and tread pads can ignite, char, or melt when exposed to the thermal environment. Plastic windows on instruments can be fogged, and glass windows can be cracked. The problems could be minimized by using reflective or thermally conducting materials for these components and by recognizing that, in most cases, reflective coatings are not compatible with camouflage requirements. Double insulation provides an effective means of raising the cable degradation threshold of electric and fiber optic cables. Before choosing alternative materials, one must be assured that the charring or the melting will produce more than cosmetic effects to the survivability of the system, particularly for small systems.

2.3.2.3 Thermal-Hardening Validation

Thermal hardening can be validated by worst-case calculations. By this method, internal temperature rise and surface temperature calculations should demonstrate that an adequate margin exists so that the system can complete its mission. Where this margin does not exist, the experimental approach should be taken.

At the present time, a newly developed, large-area, thermal simulator, the "flash bulb" technique, is being evaluated by the Army Ballistic Research Laboratories, Aberdeen MD. It employs large plastic bags filled with oxygen gas and aluminum dust. Early indications are that this method will be adequate for moderate-size structure illumination to thermal radiation threat criteria. Tests have been performed using this thermal simulator with shock tubes to evaluate the blast-thermal synergism. Early results indicate that this experimental technique will be quite valuable in assessing this synergism. Other thermal simulation techniques using pyrotechnics are being explored, but are not as promising as the flash bulb technique.

2.3 3 Initial Nuclear Radiation

Materials, electronic piece parts, and, hence, system performance can be seriously affected by exposure to initial nuclear radiation. The specific radiation components of interest in this section are the neutrons and the gamma rays that are transported to the system.* These pulses of radiation produce effects that are commonly referred to as "transient radiation effects" (TRE). The TRE can be both permanent and transient. The principal effects of interest occur in electronic systems, particularly in semiconductor and optical materials.

Regarding the environment, the effects of the interaction of the weapon's output with the air modify the neutrons' spectra and delay the gamma pulse. An additional modification or attenuation of the initial nuclear radiation can occur when this radiation interacts with the system. However, these modifications are not significant for most structures, except for armored vehicles or thick (greater than 25 cm) earthen or concrete structures. They are not significant because the gamma-ray attenuation increases with increasing material density and thickness. On the other hand, neutron attenuation is greatest for materials that contain hydrogen, such as damp earth, concrete, or any low atomic number (Z) substance.†

2.3.3.1 Transient Radiation Effects

Radiation-material interactions.--Two atomic changes can result from the interaction of nuclear radiation with matter: atomic displacement effects and ionization effects. For displacement effects, atoms must receive sufficient energy to be dislodged from their normal sites. Heavy particles such as neutrons are efficient producers of displacement effects because of their kinetic energy. Within the material, displacements disrupt the orderly or stable arrangement of the atoms. Near these disrupted sites (defects), the electronic energy levels are perturbed. These perturbations influence the material's electronic properties and are important considerations for solid-state devices.

Ionization effects are produced by interactions of the nuclear radiation particles or photons (gamma rays) with atoms. These interactions result in free electrons and holes (parent ions). Some of

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**Even though a significant percentage of the nuclear weapon energy is in the x-ray output, these x rays are readily absorbed in the atmosphere. For systems on or near the ground and at slant ranges of interest to tactical Army systems, the direct x-ray effects do not constitute a threat.*

†Iron is not a low-Z material, but, because of the thickness of armored vehicles, attenuation factors of 0.5 to 0.9 are possible.

the electrons released in the material have sufficient energy to escape from the material and add to the external radiation flux (secondary electron emission).* However, most of the electrons released by ionization events lose their energy in the material, form a mobile population of electrons, and leave behind holes at thermal energy. The prompt, radiation-induced release of electrons and holes produces a current that in certain materials can be measured in an external circuit. Some electrons and holes are trapped in the material and change the electronic and optical properties of the material.

To quantify each of the effects, one must relate the effects to a description of the radiation environment. The description appropriate to displacement (neutron) effects is different from that for ionization effects. For the latter, specifying the radiation absorbed in terms of the energy deposited in the material in units of rad (material) is appropriate, such as rad (Si). For displacement effects, the description requires that the number density and the energies of the incoming neutrons be related to the cross section versus energy for displacements in the material. The accepted convention is to specify the neutron environment as a fluence in neutrons per square centimeter (1-MeV damage equivalent in the material).† For the material of most interest, Si, the technique for calculating the 1-MeV equivalence is described by Rudie.[10]

Since all electronic systems contain semiconductor devices, but all of these systems do not contain electro-optical components, the discussion is divided into two parts: semiconductor devices and electro-optical components.

<u>Neutron effects in semiconductors</u>.--The most sensitive components of an electronic system to TRE are generally the semiconductor devices. Neutron-induced displacements produce three major effects in the semiconductor device material: (1) minority-carrier lifetime degradation, (2) majority-carrier removal, and (3) majority-carrier mobility decrease. For fluences below 5×10^{12} n/cm^2, the important effect is minority-carrier lifetime degradation. For example, this degradation causes current gain degradation in bipolar transistors. Those device technologies that are insensitive to this effect can be eliminated from further consideration. Such device technologies include junction field-effect transistors, all types of metal oxide semiconductor (MOS) devices, microwave avalanche diodes, and Varactor diodes. On the

[10]*Norman J. Rudie, Principles and Techniques or Radiation Hardening, 2, Western Periodicals Co., North Hollywood, CA (1976), 20-14.*

**This is the source of internal or system-generated EMP.*

†*For notational ease in this paper, "n/cm^2" is used in place of "n/cm^2 (1-MeV damage equivalent in Si)."*

other hand, technologies associated with bipolar transistors, bipolar integrated circuits (IC's), diodes, and various types of thyristors may be quite sensitive to minority-carrier lifetime variations.

Consider first the effects on bipolar transistors. Neutron-induced displacements in bipolar transistors can cause current gain degradation. The extent of the degradation within a device depends principally on the neutron fluence, the operating point of the device, and the time following the exposure (some damage anneals out). Normally, devices with larger gain-bandwidth products (f_T's) suffer smaller neutron-induced gain degradations. A general rule is to use transistors having f_T values greater than or equal to 50 MHz where feasible and to bias them to operate near the peak current gain. This rule ensures that there will be little or no adverse response to the effects of neutrons at fluences of interest to most tactical systems.

Saturation voltage changes of transistors as a result of neutron irradiation may be as important as gain changes in some circuit applications, such as power supplies. In contrast to the neutron-induced changes in gain when the gain decreases with increasing neutron fluence, the saturation voltage increases with increasing neutron fluence.

For diodes, the neutron-induced changes are typically small. However, some parameters change measurably in some devices. For example, high-power rectifier diodes may increase somewhat in forward voltage drop, and temperature-compensated precision reference diodes may have small reverse voltage changes. Specific device data are required to determine the importance of these changes to the circuit of interest.

In bipolar digital IC's, neutron irradiation causes the fan-out capability (the number of gate inputs that can be coupled to an IC's output) to be reduced. This reduction occurs because the changes in the output transistor's parameters reduce the maximum current that the transistor can sink. In addition, the high-state output and low-state output voltage levels may degrade somewhat so that the protective voltage difference (guaranteed noise voltage margin) between the two levels is reduced. Thus, the IC may be more vulnerable to noise-induced changes in logic state after irradiation. These changes occur at neutron fluences greater than or equal to 5×10^{12} n/cm^2.

In analog IC's, the neutron-induced changes can result in some loss of IC gain, a reduction in the f_T, changes to the input offset voltage, and a reduction in the ability to supply current to a load. Because of the small junction areas, high gains, and large negative feedback used in most designs, analog IC's typically are not a problem for neutron fluences less than 5×10^{12} n/cm^2. Exceptions may be extremely high-performance analog IC's or those IC's that use lateral PNP transistors for gain elements. These lateral PNP transistors are typically of lower-frequency design than the NPN transistor. The high-performance analog IC's include low-power, high- input-impedance operational amplifiers and high-slew-rate operational amplifiers.

Some unijunction transistors (UJT's) degrade significantly at tactical levels of neutron fluence. However, it is possible to use UJT's in circuits if the design margin of these circuits is sufficient to accommodate the neutron-induced changes. Thyristors, including silicon controlled rectifiers (SCR's), may be vulnerable to neutron damage at fluences as low as 10^{11} n/cm^2. The primary damage effects are increased required gate current and degraded gain. These can usually be compensated for by providing higher gate drive. However, the determination of the proper design margins will likely depend on experimental response data.

The effects of neutrons are not dependent on the device being biased during the irradiation. Although this factor simplifies the experiments at nuclear reactor facilities, the equipment is susceptible during the complete stockpile-to-target sequence. This susceptibility is in sharp contrast to other TRE that are very much dependent upon the semiconductor devices being biased.

<u>Total dose effects in semiconductors</u>.--The total ionizing dose effects on electronics at the levels of interest to field Army equipment can produce several effects; one of these is circuit latch up. Latch up is an unusual, undesired, stable mode of circuit action that, once initiated, can be altered only by removing the external primary power. During latch up, larger than normal currents continue to flow through the latched device until the primary power is removed. In some circumstances, this continuance could lead to device burnout. From an operational standpoint, an additional problem occurs since a latched-up device cannot respond to input signals. Implicit in the condition for latch up is that the equipment is powered. Therefore, latch up is not a threat when the system is in storage, transit, or any scenario where the system is unpowered.

The latch-up phenomenon occurs at very low doses ($\approx$10 rad (Si)), but only for high dose rates (greater than 10^7 rad (Si)/s), and is initiated in four-layer semiconductor junctions (PNPN). Because of this unique junction requirement, bulk complementary metal oxide semiconductors (CMOS's), junction-isolated (JI) bipolar IC's, and SCR's are latch-up candidates. Whereas direct current (dc) applications of SCR's have a certain and predictable latch-up response to ionizing radiation, the alternating current (ac) applications are not always as predictable. Because latch up is so rapid and can cause large instantaneous currents to flow, even ac applications of SCR's are suspect. It is best to avoid SCR circuits. If latch-up susceptible devices (SCR's and certain types of JI and CMOS IC's) cannot be avoided, adequate current limiting on the power supply buses can be provided to reduce the probability of latch up and prevent device burnout. Automatic circumvention and manual cycling to restore normal system operation are other alternatives.

Latch up in JI bipolar IC's has been observed in only a few part types. On the other hand, bulk silicon CMOS IC's are more likely to latch. Unfortunately, these technologies comprise the bulk of the IC's being manufactured today. Before using these part classes, one should determine whether latch up will occur in the part type under consideration. This occurrence is best determined with ionizing rate experiments on the chosen IC's or through the literature. Once latch up has been identified as a problem, there are several possible solutions. The simplest is to have the operator turn the power off and then back on. Although this is an inexpensive approach, it has the fault of requiring the operator to have the presence of mind to perform this routine. A fault indicator might resolve this problem. An automated alternative is an electronic detection scheme using an SCR to act as a crowbar to the power supply; 1 s later, the power is turned on. A more desirable solution is to limit the current to the IC's from their power supply by the addition of a small series current-limiting resistor. The value of this resistor should be chosen to limit the current below that value necessary to sustain latch up. In some cases, an alternative device may be available off the shelf that will not latch since designs (topology) vary among vendors. Dielectrically isolated (DI) IC's can be substituted for JI IC's. For the most difficult cases, there are special manufacturing techniques available that eliminate latch up in CMOS's. Among these techniques are gold doping, mask layout design (for example, eliminating four-layer structures or preventing first and third junctions from being forward biased), and even neutron irradiation. (Neutron irradiation and gold degrade the minority carrier lifetime of the parasitic transistors and thereby preclude latch up.)

Ionizing radiation also can change the semiconductor-insulator interface of devices. Bipolar devices typically have a passivation layer where such changes can occur. Fortunately, in bipolar IC's, this is a second-order effect, and, for the total dose levels of interest in tactical systems, this effect can be neglected except for IC's operated at much lower than normal currents. On the other hand, in MOS IC's, this is a first-order effect and is manifested as an induced threshold voltage shift. The threshold voltage shift is a permanent change. Its magnitude is a function of the gate-bias voltage and the material properties of the gate insulator. In CMOS/SOS devices,* there is an additional problem of increased back-channel leakage current. This can increase the current drain in the device by orders of magnitude at doses greater than 10^4 rad (Si).[11]

Hardened MOS IC's, by using a variety of techniques, have been fabricated. Such hardened MOS IC's have performed satisfactorily at radiation doses greater than 10^6 rad (Si). When commercial or custom MOS IC's are used, particularly dynamic n-channel metal oxide semiconductor (NMOS) or CMOS large-scale IC's, the variation in the total dose response within the part type is determined (usually experimentally) and taken into account before the final decision to incorporate these IC technologies in the design of a system. At this time, it is likely that custom or commercial CMOS IC's with acceptable radiation response characteristics can be readily purchased. However, the same is not true of current NMOS technology. This technology should be avoided if it is at all possible. If NMOS technology must be used, the piece-part response data must be obtained. These data must be from various date codes of the vendor selected. If the response is acceptable, then that IC type should be procured from the same vendor under military specifications that will control manufacturing changes that might lead to degradation of response characteristics.

A recently proposed alternative solution would permit the use of NMOS microprocessors in modest total dose environments.† It is well known that the total dose response of MOS IC's is a function of the applied bias.[12] If a circuit that is designed to detect gamma rays and remove bias from the NMOS microprocessor for approximately 10 s is included in the system, then the survivability of the system may be increased by an order of magnitude. Although this concept has not been tested, it is considered a feasible solution.

A consideration in the radiation evaluation of MOS IC's is the time to deliver the total dose. Radiation-induced photocurrents in the Si substrate can momentarily reduce the field across the gate oxide. This decrease affects the production and the transport of charges in the oxide, which in turn influence the device threshold voltage shifts. For

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[11] *J. R. Srour, S. Othmur, and S. C. Chen. Leakage Current Phenomena in Irradiated SOS Devices, IEEE Trans. Nucl. Sci., NS-24 (December 1977).*

[12] *David K. Meyers, Ionizing Radiation Effects on Various Commercial NMOS Microprocessors, IEEE Trans. Nucl. Sci., NS-24 (December 1977).*

**A CMOS made on a sapphire substrate is designated "CMOS/SOS," where "SOS" is silicon on sapphire.*

†William Seliek, Directorate of Atomic Weapons Development, Ministry of Defense, London, UK, private communication.

this reason, the total dose threat specification should include the time history (see table 1 as an example). This time history should be used when designing a system or choosing an ionizing radiation simulator for testing. Based on the threat, our recommendation is to use a ^{60}Co source in contrast to a pulsed source as a total dose simulator and to accumulate the specified dose within 10 s, if possible.

Dose-rate effects in semiconductors.--The basis for dose-rate effects in semiconductors is that ionizing radiation generates electron-hole pairs. In silicon, 1 rad absorbed can produce greater than 10^{13} electron-hole pairs/cm^3. The current, which is produced in a PN junction by ionizing radiation, is called the primary photocurrent. This primary photocurrent can be multiplied within transistors (due to their inherent current gain), multiplied still further by the rest of the circuitry, and appear as an amplified or a secondary photocurrent.

The dose rate threat in the extreme has a FWHM of 150 ns. For devices whose dose rate response depends on pulse width, calculations and tests must use this extreme value of pulse width. For devices and circuits whose dose rate response depends on current, pulse width of $\leq$150 ns are recommended.

The total photoresponse of a transistor or an IC in a circuit depends on the circuit parameters, the circuit design, and the gain of the device. The isolation of a device from the power supply and the circuit gain are the factors that determine the power dissipated in the device and the size of the induced signals. Circuits with inductors or transformers can provide pulsed response in a high-rate, ionizing environment that will exceed the power and voltage capabilities of devices.

The ionizing dose-rate effects include transient false signals, device burnout, semiconductor logic upset, and reversible and irreversible changes of state. Most Army equipment does not have an operate-through requirement for nuclear survivability. Transient false signals and logic upsets can be compensated for. For example, the bad data can be discarded, a retransmission can be requested, or a way to reestablish synchronism or stored information can be provided. In some military equipment, some degree of logic upset protection is provided for since commonly occurring power transients and outages can produce similar effects. In systems in which stored information is inviolate, special precautions must be taken to minimize radiation-induced photocurrents. Magnetic storage devices (disc, tape, core, or plated wire) can survive greater than 10^9 rad (Si)/s without stored data being scrambled. Another option is CMOS/SOS memories. These devices have been demonstrated to survive upset beyond 10^{10} rad (Si)/s.[13]

[13] *George Brucker, Characteristics of CMOS Bulk and SOS Memories in a Transient Environment, IEEE Trans. Nucl. Sci., NS-24 (December 1977).*

Where there is an operate-through requirement, the nuclear-induced transients must be sensed, and the appropriate electronic state must be established and reestablished automatically. This circumvention technology has been developed and extensively applied to strategic missile systems.[14,*] However, this approach can be expensive.

Prevention of semiconductor burnout in discrete devices and IC's is strongly associated with reliability considerations and good design practices. There are two types of burnout: metallization burnout and junction burnout. Both types are caused by the large currents induced in the circuit by the gamma pulse. Most metallization burnouts are due to defective metallization, which can be avoided by proper device reliability design methods. To prevent currents able to produce burnout, it is necessary to properly isolate the piece part from its primary source of current, that is, its power supply. Proper isolation is normally achieved with appropriate current limiting techniques.

As is discussed in section 2.3.4, the nuclear EMP can burn out devices through currents coupled into the electronics. Prompt gamma rays arrive almost simultaneously with the nuclear EMP. Some early work has indicated that the effects of these two environments can be synergistic in terms of the burnout thresholds of bipolar devices.[15] Moreover, in analog IC's, the gamma-ray-induced increase in conductivity may lead to EMP-induced junction failures inside the IC where these failures might not have occurred without the simultaneous ionizing radiation. The best way to mitigate this problem is to provide adequate EMP protection. These protection techniques are discussed in section 2.3.4.

Radiation response of electro-optical components.--The transmission of information in fiber optic (FO) cables is permanently degraded at low total ionizing doses due to an increase in optical absorption. This degradation is a function of the cable composition, the length of the cable, the ambient temperature, and the carrier wavelength to be transmitted. The degradation of FO cables can be reduced by judicious choice of materials, use of the shortest length possible, and selection of the carrier wavelength for minimum absorption. The ionization pulse produces a transient increase in absorptivity and a

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[14] *Richard K. Thatcher, ed., TREE (Transient Radiation Effects on Electronics) Handbook (U), 2, 3rd ed., Battelle Columbus Laboratories, Columbus, OH, DNA 1420H-2 (May 1972). (Defense Documentation Center AD 519563, AD 528947) (SECRET RESTRICTED DATA)*

[15] *D. H. Habing, The Response of Bipolar Transistors to Combined EMP and Ionization Environments, IEEE Trans. Nucl. Sci., NS-17 (December 1970), 360-363.*

**See Selected Bibliography.*

transient luminescence in FO cables. Usually, these transient effects last less than 1 s. The impact of both the permanent and transient effects are system dependent and can be worsened by low temperatures.

Of the various types of lasers, only the yttrium alumimum garnet (YAl_2O_3):neodymium (YAG:Nd) laser is of concern to nuclear survivable tactical systems. The YAG:Nd system output energy degrades at total-dose levels as low as several hundred rad (YAG). The energy output is a measure of the effective range of a laser system. If the system is designed to operate at or near the inversion (lasing) threshold, small radiation-induced changes can turn off the laser. The cause of these changes is the ionizing radiation-induced absorption in the crystalline laser medium. Repeated pulsing of the laser can bleach (remove) most of the induced absorption. The effect of this degradation can be minimized by providing more optical input power to the laser crystal.

Some light-emitting diodes (LED's) begin degrading at neutron fluences less than 10^{12} n/cm^2. For example, GaAs:Si LED output degradation can be as much as 10 percent of the preirradiation value at 10^{12} n/cm^2 and 90 percent at 5×10^{12} n/cm^2. In LED applications, one should ensure an adequate design margin. The designer should also include provisions for dose-rate-induced light spikes.

All optical detectors respond to the dose-rate environment with a pulse output. Current limiting should be provided to protect against detector burnout. Phototransistors, some Si detectors, and InSb photovoltaic detectors are degraded by neutron fluences less than 10^{12} n/cm^2. For example, some phototransistors are degraded 10 percent at 10^{11} n/cm^2, and photovoltaic Si and photovoltaic InSb are degraded ≈ 10 percent at 5×10^{11} n/cm^2. In most applications, one should be able to design around this degradation by allowing for the anticipated degradation or, in the case of the Si PIN (P region, intrinsic region, N region) diodes, by biasing the device into depletion or otherwise selecting an alternative detector.

2.3.3.2 Circuit and System Transient Radiation Effects Hardening and Validation

This discussion of TRE has indicated a variety of device responses to the constituents of the initial nuclear radiation. Table 2 summarizes the effects on semiconductor devices and electro-optical materials.

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[16] *J. J. Halpin, A Progress Report on the Transient Radiation Effects on Laser Materials, FY71, Naval Research Laboratory NRL Memorandum Report 2337 (30 June 1971). (Defense Documentation Center AD 888249L)*

TABLE 2. SUMMARY OF TRANSIENT RADIATION EFFECTS

Device class	Permanent effects	Transient effects
Bipolar		
Transistor	Current gain decrease Leakage current increase Saturation voltage increase Junction burnout	Induced photocurrent
Unijunction transistor	Valley voltage increase	—
Diode	Forward voltage increase Leakage current increase	Induced photocurrent Reverse voltage change
Thyristor	Holding current increase Gate firing current and voltage increase Breakover voltage increase Induced turn on	—
Integrated circuit		
Digital	Logic level shift Fan-out decrease Input threshold voltage shift Latch up	Logic upset*
Analog	Gain decrease Offset voltage shift Offset current shift Latch up	Induced photocurrent Output voltage change
Complementary metal oxide semiconductor		
Bulk	Threshold voltage shift Latch up	Logic upset*
Silicon on sapphire	Threshold voltage shift Increase in standby current	Logic upset, but outside range of interest
N-channel metal oxide semiconductor	Threshold voltage shift	Induced photocurrent Logic upset*
Fiber optics	Optical absorption increase	Optical absorption increase Transient luminescence
Laser	Output power decrease	Output power decrease
Light emitting diode	Light output degradation	Induced light spikes
Detector	Output decrease	Current pulse

**This effect can cause permanent change; for example, data in memory are scrambled and must be reentered. The change can also be temporary; for example, data processing can be interrupted by a radiation-induced transient, and, after the transient has died out, normal processing is resumed.*

The procedures that are usually used to overcome TRE are scattered throughout section 2.3.3.1. Table 3 summarizes these procedures. The X indicates a potential area of vulnerability to an initial nuclear radiation constituent at tactical levels. The hardening procedure varies with both the device type and the radiation constituent. This section summarizes the hardening procedures and validation methods to be used for each constituent.

Neutron hardening procedures and survivability validation.--The neutron response of a system can be inferred from the response of the devices in the system's circuits. To harden the circuits and, therefore, the system itself, it is necessary to understand and obtain data for the response of the devices in the system. This knowledge along with engineering models for semiconductors that represent the electrical and neutron response characteristics of these devices can be used to determine the response of the circuit.

The degradation of the devices induced by neutron radiation must be added to other degrading factors such as temperature, parts variability and reliability, in the design of circuits. Specifically, the neutron-radiation-induced degraded values of device parameters must be used as starting values before the design margins and other degrading factors are added.

As table 3 indicates, the hardening approaches for neutron irradiation are the proper choice of devices (for example, selecting bipolar transistors with an f_T greater than or equal to 50 MHz) and adequate design margins (for example, using digital bipolar IC's at less than their maximum fan-out).

Design considerations and piece-part response information should be combined with hand or computer analyses to determine the circuit survivability. Circuit response calculations should be combined to determine subsystem* and then system level response. Where piece-part data or circuit predictions indicate narrow survivability margins (in general, less than a factor of two), a statistically significant number of samples of the parts or the circuit should be tested. For a system's neutron response, piece-part data coupled with circuit analysis can provide acceptable confidence in the system's survivability.

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*"Subsystem" means a combination of circuits that can stand alone and perform a very specific function, such as a power supply or a range finder.

TABLE 3. TACTICAL LEVEL TRANSIENT RADIATION EFFECTS ON DEVICES

Device class	Neutron irradiation		Total-dose irradiation		Dose-rate irradiation	
	Vulnerability	Hardening approach	Vulnerability	Hardening approach	Vulnerability	Hardening approach
Bipolar						
Transistor						
High power	X	Use device with gain-bandwidth product >50 MHz and operate near peak current gain.	-	-	X	Limit current.
Low power	-	-	-	-		
Unijunction transistor	X	Design margins.	-	-	-	-
Diode					-	-
Power	-	Design margins.	-	-		
Precision	X	Design margins.	-	-	-	-
Thyristor	X	Design margins.	-	-	-	-
Integrated circuit					X	Limit current.
Digital	X	Avoid maximum fan-out.	-	-	X	Choose proper device type or operational fix.
Analog	X	Select device type or screen devices.	-	-	X	Choose proper device type or operational fix.
Complementary metal oxide semiconductor						
Bulk	-	-	X	Choose proper device type.	X	Choose proper device type or operational fix.
Silicon on sapphire	-	-	X	Choose proper device type.	-	-
N-channel metal oxide semiconductor	-	-	X	Avoid use if possible.*	X	Avoid use if possible.*
Fiber optics	-	-	X	Choose proper material and carrier wavelength; minimize length.	X	Choose proper material and carrier wavelength, minimize length.
Laser	-	-	X	Increase optical input power.	-	-
Light-emitting diode	X	Design margins.	-	-	-	-
Detector	X	Design margins	-	-	X	Limit current.

If N-channel metal oxide semiconductor must be used, then response data for that device must be obtained. That device should then be procured from the same vendor under military specifications.

Total-dose hardening procedures and survivability validation.--As indicated in table 3, total dose at tactical levels does not affect many of the common classes of devices such as bipolar diodes, transistors, and IC's. For those that are affected, much of what applies to hardening against neutrons applies also to hardening against total dose. In other words, the response of piece parts must be determined experimentally. The response of the circuit itself is then determined from these piece-part data.

Hardening approaches for total dose include proper choice of devices (such as purchasing CMOS devices with acceptable total-dose response characteristics or choosing the proper material for fiber optics) and adequate design margins (such as increasing optical input power for lasers or minimizing the length and choosing the proper carrier wavelength for fiber optics). But the NMOS device constitutes a special case. If it must be used, then device response data must be obtained. If the response is acceptable, then that device should be procured from the same vendor under military specifications.

Since latch up occurs at very low doses, but only at high dose rates, the discussion of the hardening procedures that prevent latch up is deferred until the discussion on dose-rate hardening.

Validation of total-dose survivability is done much the same as for neutrons. System total-dose validation is treated on a piece-part basis. Piece-part data coupled with an analysis of circuit or subsystem design margins can provide acceptable confidence in the system's survivability.

Dose-rate hardening procedures and survivability validation.--Dose rate affects many more device classes than total dose. These effects on systems must be treated on a parts, circuit, and subsystem or system level and cannot be strictly limited to piece-part response. In general, analytical techniques are not high confidence approaches to this constituent of the initial nuclear radiation.

As indicated in table 3, the hardening approaches to dose-rate effects are proper choice of devices (such as using CMOS devices that incorporate gold doping or dielectric isolation or avoiding those rare JI bipolar IC's that are prone to latch up) and current limiting (such as isolating the device from its power supply with an appropriate current limiting impedance). Table 3 indicates also that consideration should be given to operational alternatives to ease the survivability requirements on the system. Such alternatives include avoiding operate-through-the-burst requirements, that is, allowing the system to be inoperative for at least 10 s or even longer, if possible; permitting the system to go into latch up and allowing for manual or automatic cycling of power (off-on); designing computers so that logic upsets can be tolerated and data can be reentered to reinitialize the computer; and designing those systems that require accurate timing or synchronization so that this timing or synchronization can be reestablished after a burst with a minimum of delay.

As a general guideline for the validation of the system's survivability to dose-rate effects, an experimental approach on the circuit or subsystem level coupled with an analysis for current limiting in the circuit design should be given preference. This may include an evaluation of the effectiveness of any operational fixes--for example, determining the time required to reenter data into a computer.

Initial nuclear radiation simulation and testing.--Certain simulators are suitable for dose-rate testing, and others are suitable for neutron and total-dose testing.[17] Our recommendations (p. 29) should be used for the selection of the appropriate simulator.

Regarding testing in general, for any constituent of initial nuclear radiation, validation tests or tests for data should be performed at the lowest level possible, that is, at the parts level as the first choice and at the system level as the last choice. In this manner, it is more cost effective to have statistically significant data, and the piece-part data can be used again to analyze systems with the same piece parts. Moreover, tests on only one system are restrictive in utility and are of no statistical significance. These single tests increase visceral confidence, ensure no oversights, and provide confidence in the analytical predictions only on this specific piece of equipment.

2.3.4 Electromagnetic Pulse

Of the four nuclear weapons effects environments discussed in this document, EMP has particular significance for military electronics. Though causing no documented deleterious effects to humans, a single nuclear event can generate an EMP capable of damaging or upsetting the electronics of a significant percentage of deployed equipment at distances considerably greater than in the other nuclear environments. For this reason, a considerable effort has been made to assure the survivability of many of the tactical Army equipments to this nuclear weapons effect. This section highlights some of the most important

[17]*TREE Simulation Facilities, 1st ed., Battelle Laboratories, Columbus, OH, DASA-2432H (October 1973). (Defense Documentation Center AD A009308)*

aspects of EMP, its effects on electronic equipment, typical generic hardening methods, and some of the universally accepted test techniques in support of validating system survivability.

Though transient, EMP differs significantly from other electromagnetic transients commonly addressed by today's system design engineers. For example, even though the EMP phenomenon is similar to that generated by lightning, the high-frequency content in an EMP signature is much larger and, generally, makes standard lightning protection inadequate. The frequencies of interest for electromagnetic interference (EMI), on the other hand, include most of the frequencies contained in EMP, yet the amplitudes associated with EMP are orders of magnitude greater than those associated with EMI. The point is that a system normally protected from lightning, EMI, and other electromagnetic transients is not necessarily protected against EMP.

However, EMP does have some characteristics in common with other transients. As with any transient electromagnetic signal, EMP couples to systems through deliberate or nondeliberate antennas or penetrates into systems through various deliberate or inadvertent apertures. Voltage and current transients able to permanently damage or upset equipment can be coupled to electronic piece parts through these means. Whether or not damage or upset occurs is determined by just how much energy is coupled to the sensitive piece parts and the damage or upset level of those piece parts. For EMP protection, a number of standard methods have been developed by the EMP community and are being used.

2.3.4.1 Electromagnetic Pulse Environments

The term "EMP" is an acronym used by the nuclear weapons effects (NWE) community to cover an enormous range of EMP signatures. Typically, EMP criteria on tactical Army equipment are given as two environments: HAEMP and LAEMP. In the following paragraphs, we identify how EMP is generated by a nuclear detonation and explain why the EMP criteria are given in two parts.

Nuclear EMP is created by the change in motion of high-energy electrons that are released by weapon-generated gamma rays colliding with molecules in the air or the ground. This complicated process occurs in a fraction of a second. It is important to know, however, that the resultant EMP signature as seen by an observer on the ground is shaped by a number of scenario parameters, which include the weapon yield and the height of burst (HOB), asymmetries in the earth's atmosphere, the location of the burst with respect to the earth's magnetic declination, and the relative distances of the observer to both the ground and the burst point. As mentioned in section 2.1, two distinct scenarios produce the two types of EMP threats. The scenario differences that concern us most are the weapon yield and the HOB.

High-altitude electromagnetic pulse.--An HAEMP is the result of a high-yield weapon typically greater than a fraction of a megaton, detonated more than 30 km above the earth. The HAEMP is represented by a plane wave of large amplitude that is less than or equal to 50 kV/m; its rapidly rising waveform (on the order of 10 ns) and decaying waveform (on the order of hundreds of nanoseconds) includes frequencies up to hundreds of megahertz. The resulting area of coverage on the surface of the earth encompasses all points within the line of sight of the burst. Figure 4 illustrates one such set of electric field contours on the continental United States for a single burst scenario. The enormous range is determined by the HOB, which in figure 4 was hundreds of kilometers, and the electric field contour distribution is determined by the magnetic declination lines.

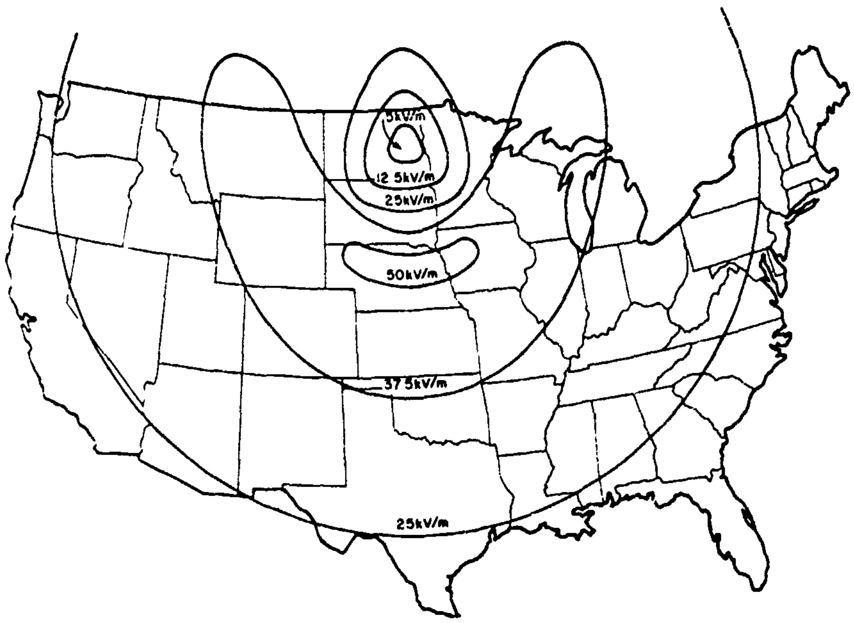

Figure 4. Equipotential contours of representative high-altitude electromagnetic pulse scenario.

The HAEMP criteria specified by ANCA are actually a composite of realizable, worst-case conditions that, in reality, cannot exist at any one place or time. The criteria are given in terms of a single free-field waveform, its polarization, and its angle of arrival. For these criteria to be used by circuit analysts in vulnerability assessments or to be simulated in system tests, the waveform must be ground interacted before it can be coupled into ground-based equipment as HAEMP. The reason is that when electromagnetic waves reflect from the earth's surface, the incident fields are modified for an observation point above the ground. This subtlety is often ignored by the analyst and by those involved in selecting HAEMP test facilities. Typical ground conductivities are 10^{-3} to 7×10^{-3} mho/m, and typical dielectric constants are 15 to 5.

Low-altitude electromagnetic pulse.--For our purposes, LAEMP is used to specify the EMP associated with nuclear detonations on or near the ground. The HOB's associated with these detonations are chosen to maximize nuclear blast damage and, at the same time, minimize fallout. Alternatively, bursts at or below the surface of the earth are used when obstructions are desired on roadways and airport runways. In contrast to HAEMP, the LAEMP resulting from these bursts is accompanied by the other nuclear weapon environments.

The LAEMP environment specified in Army system nuclear survivability criteria is calculated for what are considered to be worst-case conditions.* The LAEMP specification includes the vertical and horizontal electric fields, the azimuthal magnetic field, and the time-varying air conductivity. The energy content of the LAEMP is significant down to about 1 kHz. The rise times are on the order of the HAEMP rise time. These conditions prevail over regions much smaller (on the order of kilometers from the burst point) than those resulting from the HAEMP described above.

A transient EMP can be induced inside a system that is exposed to the gamma radiation from a nuclear burst. This electromagnetic energy is associated with the pulse of Compton electrons emitted from the walls of the system enclosure and from materials within the system. The effect is known as system-generated electromagnetic pulse (SGEMP).

Experiments and calculations have shown that the SGEMP fields generated in large structures, such as a communications shelter, are on the order of 10 percent of the unshielded external EMP (that is, 2 to 5 kV/m). Since these SGEMP fields follow the immediate radiation pulse of the weapon, a much larger portion of their energy is at frequencies above 50 MHz than is EMP energy.

2.3.4.2 Electromagnetic Pulse Effects on Electronic Equipment

Army communications and weapons systems generally share electrical characteristics that make them effective couplers of EMP. Vehicle, missile, or electronic shelter skins; electronic subsystem

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**Recent findings at the Harry Diamond Laboratories indicate that this may not be true. See T. Wyatt and R. Gray, Near Surface Burst EMP, Proc. DNA Seminar on EMP Environments and Hardening (5 October 1977).*

enclosures; cables and field wire; and headsets--all can act as unintentional antennas, and, although inefficient, they can provide good transmission paths for EMP-induced currents. Intentional antennas, particularly those designed for frequencies less than 100 MHz, are especially effective EMP couplers.

The EMP coupling of a radio can be configured for a manpack, a vehicle, or an aircraft. In the manpack configuration, assuming a simple battery-powered radio with an integral antenna, the coupling sources are direct penetration through the case and antenna coupling. In the vehicular configuration, the antenna is mounted at some distance from the radio, and power may be supplied from the vehicle alternator. The antenna and power cables, which run across a conductor (the vehicle body), can have currents injected directly or indirectly (induced by the vehicle skin currents). In the aircraft configuration, the antenna and the radio are separated, and power is supplied by the engine alternator. However, some electromagnetic shielding for the connecting cables may be provided by the body if it is a conductor or by a metal conduit when one is used.

Voltage and current pulses injected into such electronic systems can burn out components or generate false signals and cause logic upset. Component burnout is a catastrophic and permanent change in a device. The burnout threshold of a piece part is, as a first-order approximation, dependent on the power handling capability of the part. Energy levels that cause component burnout and circuit upset are summarized in table 4. The levels in the table are for the energy actually dissipated in the device itself. To cause burnout or upset, this amount of energy must be coupled into the component either directly or indirectly.

If the component is directly connected to wires entering the system, it is part of an interface circuit, and the energy collected by these wires is directly coupled to the circuit components. If a component is not part of an interface circuit, significant energy can still be coupled indirectly to low-impedance circuits if there is a wire loop. Magnetic fields, particularly low-frequency fields, can penetrate enclosures and induce currents in these wire loops. Certain grounding techniques are another source of indirect coupling: inadvertent loops can be created as a coupling source for the magnetic fields, or potential differences can be created by using multipoint grounds. Also, vehicle body or cable shield currents, created by the EMP, can induce currents in adjacent conductors. This means that even shielded cables can have significant transients induced on the inner conductors. The conclusion is that system response to the EMP is a function of both coupling sources and piece-part susceptibilities. However, the priority in determining system vulnerability should be placed on coupling analysis with consideration of the signal attenuation factors provided by various shields.

TABLE 4. MINIMUM ENERGY REQUIREMENTS

Function	Device	Minimum energy (J)
To cause burnout	Microwave diode	1×10^{-7}
	Analog integrated circuit	8×10^{-6}
	Field-effect transistor	1×10^{-5}
	High-speed switching diode	2×10^{-5}
	Switching transistor	5×10^{-5}
	Digital integrated circuit	8×10^{-5}
	Tunnel diode	5×10^{-4}
	Rectifier diode	6×10^{-4}
	Relay	2×10^{-3}
	Silicon controlled rectifier	3×10^{-3}
	Microammeter	3×10^{-3}
	Audio transistor	5×10^{-3}
	Vacuum tube	1.0
To cause circuit upset	Integrated digital circuit (flip-flop)	4×10^{-10}
	Discrete component digital circuit (flip-flop)	1×10^{-9}
	Memory core	3×10^{-9}

The phenomenon of SGEMP should be considered along with external EMP and other direct radiation as part of the total nuclear effects threat in situations for which radiation dose-rate levels of 10^7 rad (Si)/s or higher are expected. However, because the internal electric fields are proportional to the size of the system, systems that are much smaller than a signal shelter, such as a radio, are in general not vulnerable to SGEMP. Rooms that are electromagnetically shielded against external EMP can be susceptible to internal SGEMP, because the EMP-induced transients can appear on other than external coupling sources. Although upset is expected, it can be minimized if a system is hardened to EMP.

2.3.4.3 System Hardening

General approach.--The decision to harden a piece of Army tactical equipment to HAEMP, LAEMP, or SGEMP must consider the equipment's criticality to the mission. That is, if a system is critical, it is not enough that a piece of contractor-furnished equipment (CFE) be hardened; all mission critical elements of the same system must be addressed, including the critical Government-furnished equipment (GFE) that might couple energy to the CFE (through connecting cables) or might be weak links in the total system. An example of such a complex system is a radio connected to GFE such as a remote antenna, a remote sensor, a printer, a display device, or communication security (COMSEC) equipment.

System hardening to assure mission survivability must consider both permanent damage and upset as potential problems. To assure that no permanent damage occurs, EMP-induced signals must not reach critical components. Electrical energy can be diverted by (1) shielding the system and treating the penetrators to eliminate EMP-induced signals on the system or (2) shunting the EMP-induced transients from critical components. Against upset, the system can be treated the same way, although it is generally treated by operational or software changes, since upset levels of the order of a few volts cannot always be eliminated in a cost-effective way by hardware changes.

Practical applications.--To define hardening requirements, a system can conveniently be subdivided into segments (zones) that are simple enough to be treated both theoretically and experimentally. The interfaces of these zones are typically the points where EMP protection is applied. Figure 5 illustrates this zoning concept. The outer surface of the system forms the interface separating the external zone (zone 0) from those within (zones 1, 2, 3). By this zonal approach, a balanced allocation of hardening can be considered no matter how big or small, simple or complex the system may be. Tactical equipment can be conveniently divided into four zones. Zone 0 is the incident EMP environment, zone 1 is bounded by the exterior skin, zone 2 is bounded by the internal cable runs and cabinets, and zone 3 is bounded by the equipment case.

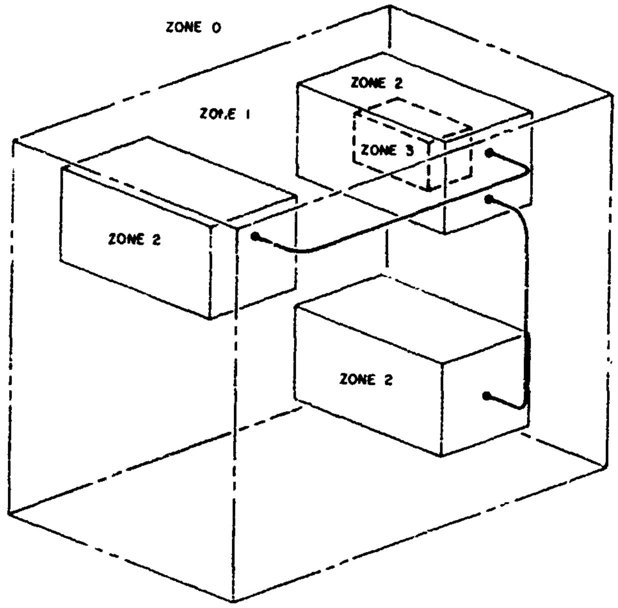

Figure 5. Generalized system topology--zonal coupling concept.

All circuits and components connected to zone penetrators must be evaluated for their vulnerability once the coupling analysis has been completed. Such evaluations may be experimental or analytical. Some experimental pulse stress data of piece-part burnout are available from Government and industry sources.[18-20] Experimental data, even though more expensive, are preferred for their accuracy. Preferred testing techniques are available in many documents generated at HDL, the Defense Nuclear Agency (DNA), the Air Force Weapons Laboratory (AFWL), and other agencies doing military research.[21-23]

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[18]*Users Manual for Supersap 2, The Boeing Aerospace Co. Seattle, WA, AFWL-TR-75-70 (1975). (Defense Documentation Center AD A022979)*

[19]*Joseph R. Miletta, Component Damage from Electromagnetic Pulse (EMP) Induced Transients, Harry Diamond Laboratories HDL-TM-77-22 (October 1977). (Defense Documentation Center AD A037564)*

[20]*Thomas V. Noon, Implementation of the Device Data Bank on the HDL IBM Computer, Harry Diamond Laboratories HDL-TR-1819 (October 1977). (Defense Documentation Center AD A046480)*

[21]*EMP Preferred Test Procedures (Selected Electronic Parts), IIT Research Institute, Chicago, IL (August 1974). (Defense Documentation Center AD 787482)*

[22]*DNA EMP Handbook (U), General Electric Co., Philadelphia, PA, DNA 2114H-1 to -4 (1971-72, rev. 1976). (SECRET RESTRICTED DATA)*

[23]*Nuclear EMP, Protection Engineering and Management Notes, Lawrence Livermore Laboratory, Livermore, CA (1970-1978).*

All circuits and components that are connected to zone penetrators and that do not meet a specified safety margin are considered vulnerable and must be made survivable. The design goal is a margin of 10 dB below the mean of the piece-part damage curve. The various hardening options available must be evaluated against the system's required functional and physical characteristics and the hardening effectiveness of the option. Consider two examples: a long multiconductor cable run and a radio antenna. For the first example, shielding and terminal protection (shunting) are viable options. Shielding may add an unreasonable weight penalty; and although terminal protection devices can conveniently be packaged in the cable connectors, they might not work so well. For the second example, deliberate radio antennas operating in the EMP band, 1 kHz to hundreds of megahertz, in-band protection is required. A typical solution is to provide a voltage clipping network, which shunts to ground the energy above a fixed level.

Table 5 lists usual hardening techniques for protection against EMP. A specific technique is used only when normal circuit or system functions are not affected. These techniques can be conveniently grouped into interface circuit modifications (1 to 8), which use either frequency or amplitude discrimination to effectively increase the circuit failure threshold; subsystem modifications (9 to 11), which reduce subsystem vulnerability by decreasing the amplitude of EMP-induced transients; system modifications (12, 13), which include hardening by software techniques and a major reconfiguration of the system's design, interfaces, operation, or deployment.

The inclusion of SGEMP generation and coupling is important to the determination of the total system response. Because of the SGEMP effect, large structures, such as communications shelters, may not be adequately protected electrically by shielding or by protection at electrical ports of entry into the shelters. Where circuit upset or computer memory degradation is operationally intolerable, hardening may be required internally; that is, cables and connectors within the shelters must be properly shielded, and terminal protection devices should be placed at the internal component boxes.

TABLE 5. SYSTEM MODIFICATIONS FOR HARDENING TO ELECTROMAGNETIC PULSE

Modification	Description
1. Component value optimization	Those component values are specified that will minimize any circuit transient, that is, use the highest allowable value of series resistors or shunt capacitors at all interface points.
2. Component substitution	Components are substituted that are less vulnerable to electrical pulse stress.
3. Filter pin connector	Multiple, low-pass filters are integrated into an interface connector shell to achieve signal rejection and internal circuit protection.
4. Interface transient buffering	External components are used such as external hardened buffer circuits to protect prepackaged circuits such as integrated circuits.
5. Terminal protection device	Suppression devices developed to handle transients associated with lightning, switching, and circuit malfunctions can be used to provide EMP protection.
6. Discrete filter	Discrete component filters are used to limit the coupled frequency to a narrow band.
7. Noninterface buffering	Automatic gain control, gain-limiting techniques, and circuit modifications prevent a circuit from entering an undesirable stable state such as latch up.
8. Other filter	Special types of filters are used such as (1) crystal; (2) ceramic; or (3) hybrid, which uses distributed passive components and quarter-wave shunt properties and incorporates suppression devices.
9. Decoupling	Circuit isolation techniques such as differential coupling, electro-optical coupling devices, dielectric waveguides, and fiber optic cables reject or isolate electrical transients.
10. Packaging	Packaging consists primarily of proper shielding and grounding. Each zone of protection should be individually shielded, and the shielding package should have a minimum of apertures. Ground loops should be avoided, and single point grounds should be used whenever possible.
11. Subsystem redesign	Techniques that must be used to achieve the required EMP survivability levels for an existing subsystem design may be incompatible with the functional and physical requirements of the subsystem. Such incompatibility dictates the need to redesign the subsystem, considering operational, software, and hardware changes.
12. Error detection	Data coding techniques such as parity checks detect errors in the data due to EMP interference and reject these date.
13. System redesign	The system may have to be redesigned to survive at an acceptable cost.

2.3.4.4 Electromagnetic Pulse Testing and Survivability Validation

Since a number of procedures are used for validating system survivability to EMP, the one selected is in part determined by the system, the subsystem, or the equipment to be tested and the nature of the EMP criteria being addressed, namely, HAEMP or LAEMP. Some available simulators are listed elsewhere.[24]

At present, no simulator exactly reproduces the HAEMP environment or even approximates an LAEMP environment. Therefore, the reliance upon a single go/no-go test to validate the system's HAEMP survivability is invalid. Furthermore, system hardness validation to LAEMP must be based upon analytical studies that are supported when possible with system level tests, including current injection and continuous-wave (cw) illumination.

The analyst must keep one important factor in mind: for the HAEMP vulnerability assessments and field testing, the ground interactions are very important for a proper evaluation of the system coupling to EMP. Free-field, radiating simulators are therefore more representative of the threat environment for systems located on or near the ground than bounded-wave simulators. With bounded-wave simulators, there are generally no ground interactions, and so they are more representative of the threat environment to systems (missiles, aircraft) in flight. Bounded-wave simulators are characterized by electromagnetic (wire) screens that confine the launched electromagnetic wave. Because of the electromagnetic boundary conditions of the wire screens and the comparatively small working volume, bounded-wave simulators also are not suitable for distributed systems (those with long interconnections).

There are two basic test approaches used to support HAEMP survivability validation studies: (1) threat amplitude testing and (2) low-level testing.

Threat amplitude testing using an HAEMP-like waveform has the advantage of providing results that do not have to be extrapolated to threat amplitude. However, there are drawbacks. High cost and possible damage to the system are the most obvious. A more subtle disadvantage is that no existing EMP simulator exactly duplicates the threat environment. Every simulator has unique and sometimes undesirable characteristics, such as anomalies in the simulator's resonance, polarity, or planarity. Therefore, when EMP simulators are used. the only valid approach is to calculate the system response for the environment produced by the simulator and for the orientation being evaluated. When there is agreement between the calculations and the experiments, the analytical

[24] *L. W. Ricketts, J. E. Bridges, and J. Miletta, EMP Radiation and Protective Techniques, John Wiley and Sons, Inc., New York (1976).*

tools can be considered valid for calculating the system response to EMP at the threat conditions.

Current injection and pulse testing are threat-or subthreat-level test techniques that use a waveform based on the waveform induced by EMP. With the current injection technique, pulsed currents and voltages are directly injected into the system where the coupling source, such as a cable, is ordinarily connected. This technique allows the evaluation of those input and output ports that have been analyzed and found to be vulnerable to the EMP threat. This technique can be adapted to simulate many HAEMP and LAEMP coupled signals; however, all coupling modes must be taken into account in the analysis that precedes these tests.

Low-level simulation facilities are designed to illuminate a system with less-than-threat amplitudes. System response data taken at such facilities must be extrapolated to the threat environment. Low-level testing can take one of several forms: less-than-threat-amplitude single-pulse testing or less-than-threat-amplitude repetitive-pulse testing, both using HAEMP-like waveforms; or cw testing, which does not use an HAEMP-like waveform. The difference between the first two methods of low-level testing is that more data per hour can be taken by the repetitive-pulse tester. The cw facility can illuminate a system with a band of frequencies (for example, the HDL cw facility at Woodbridge, VA, covers 1.5 to 250 MHz), one frequency at a time, for both horizontal and vertical polarizations. Transient responses of systems under test are computed from Fourier analysis of the cw data. The cw approach to system response measurements is more easily automated than pulse testing; hence, the problem of representing the system's response in terms of accurate equivalent circuits for HAEMP analysis is simplified. The cw approach can be applied to the LAEMP analysis directly if the effects of time-varying air conductivity can be ignored. If air conductivity is a problem, then its effect must be accounted for by additional analysis.

Electromagnetic scale modeling is another test method whereby the system, all its electromagnetic parameters, and the threat amplitudes and frequencies are scaled. This technique is useful for preliminary evaluations of distributed systems such as large communications complexes, especially for determining worst-case orientations and coupling mechanisms.

In conclusion, no one testing technique that is unsupported by analysis is effective in validating system survivability to EMP. In fact, for most EMP vulnerability and survivability programs, several experimental techniques are combined with rigorous analytic studies to arrive at a low-risk evaluation of a system. The HAEMP and LAEMP environments and coupling mechanisms are much too complex to expect single go/no-go tests to be adequate for system response evaluation and validation.

3. MANAGEMENT CONSIDERATIONS

3.1 Nuclear Survivability in Life Cycle

The life cycle of Army systems consists of four phases: (1) concept, (2) validation, (3) full-scale development, and (4) production and deployment. This section is a general discussion of the nuclear survivability considerations for the life cycle model. A more thorough discussion of the management considerations is in volume II of this report.[2]

In each phase of the life cycle, there are a hardware effort and a planning effort. Generally, the hardware effort is performed under contract. The planning effort is organized by the materiel developer and the combat developer. The planning and the documentation in one phase are designed to influence the hardware development and procurement in the next phase.

For system nuclear survivability, it is necessary to perform the studies and the feasibility assessments for nuclear survivability in the concept phase and to prepare to build survivable hardware for the validation phase. These preparations include the generation and the incorporation of the nuclear survivability criteria in test and program overview, planning, and documentation aspects of the concept phase.

In the validation phase, the best effort should be made to design and verify the system to survive a nuclear attack. It may not always be possible or desirable to completely implement nuclear survivability in this phase, for the reason that better materials, devices, or technologies may not be available until the next phase. The rationale, however, is to make as total a commitment to nuclear survivability as early as possible to avoid drastic changes in the basic design of the equipment in the next phase of development. The issue here is that nuclear survivability is affordable when implemented early in the system life cycle.

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[2] *Joseph J. Halpin and John P. Swirczynski, Nuclear Weapons Effects on Army Tactical Systems, Vol. II, Management, Harry Diamond Laboratories HDL-TR-1882-2 (May 1979).*

Preparation for system production and maintenance should begin in the validation phase and be updated in the following phases. These preparations should include the documentation of those items that will need to be preserved to retain the system's nuclear survivability up to and including deployment.

In the full-scale development phase, the objective is to maintain the survivability already designed and verified by controlling the changes to the system. During this phase, the incorporation and the verification of those aspects of nuclear survivability not completed in the previous phase must be finished.

In the final phase, production and deployment, the greatest concern is to prevent those changes that would compromise the system survivability. Any changes in the hardware or operational concepts should be reflected in the final documentation for the system, and, as appropriate, these documents should reflect the latest nuclear survivability considerations.

3.2 Survivability Costs

If a system's cost were doubled or tripled by nuclear survivability considerations, then those cost increases would have a profound effect on the program. However, at tactical threat levels, the incremental costs for obtaining nuclear survivability are typically only a small percentage of the overall system costs. The survivability cost estimates should be 1- to 5- (max 10-) percent typical increments for research, development, testing, and evaluation (RDTE) and 1- to 3- (max 5-) percent typical increments for unit production. The system developer, the contractor, and the nuclear survivability community must analyze the trade-off to determine the impacts of various hardening methodologies and operational considerations on costs, survivability, and effectiveness. They must do so to decide on an optimal balance between cost and survivability while maintaining the required performance.

3.3 Nuclear Expertise

All too often, the various organizations that evaluate, plan, and recommend developmental survivable hardware do not use the available nuclear expertise. Without it, the system will survive a nuclear attack only by accident. The expertise of the Government NWE community should be called upon at the key planning, testing, and evaluating points in the life cycle.

The need for nuclear expertise exists in all phases of the life cycle. In the concept phase, the Test Integration Working Group and the Special Task Force or the Special Study Group must use nuclear expertise since their planning documents (the Coordinated Test Plan--CTP--and the

Concept Formulation Package--CFP) are critical to the system's nuclear survivability. In fact, nuclear survivability considerations must be included even in the documents that form a basis for the CTP (the Independent Evaluation Plan for testing, the Test Design Plan, and the Outline Test Plan), as well as those that make up the CFP (the Trade-off Determination, the Trade-off Analysis, the Best Technical Approach, and the Cost and Operational Effectiveness Analysis). During all phases, the Army Materiel Systems Analysis Activity should use Government nuclear consultants for both the nuclear effects test planning and the evaluation of the test results. The system developer should use Government nuclear effects expertise to develop the contract packages and to evaluate the bids. After the contract awards, the system developers should seek advice from Government or industry nuclear effects experts on nuclear effects matters. During the production and deployment phase, those groups such as the Configuration Control Board, which evaluates and implements proposed changes (that is, Engineering Change Proposals and Product Improvements), must also consult with nuclear effects experts to ensure that the changes do not jeopardize the survivability of the system. The audits (the Functional Configuration Audits and the Physical Configuration Audits) must be conducted by using nuclear expertise to ensure that the final production version of the system does meet the required nuclear survivability levels.

Within the Army, several organizations support the various aspects of nuclear survivability. The user community is represented by ANCA. The material developer has an NWE lead laboratory at HDL. The nuclear survivability programs throughout the Army are coordinated by the Nuclear Weapons Effects Program Office (NWEPO) in HDL. Support for the nuclear blast and thermal radiation is obtained from the Armament Research and Development Command, Ballistic Research Laboratories. In addition, HDL has experts who are specifically available to support system developers on NWE matters, the Nuclear Effects Support Team (NEST). It is funded by DARCOM and available to the materiel developer through NWEPO.

Throughout private industry, nuclear experts can provide technical support on a consultant or program basis.

3.4 Supporting Documentation

Some documentation does exist that is useful in the successful management of nuclear survivable systems. Existing documentation is compiled and discussed in volume II of this report.[2] That document includes some NWE Data Item Descriptions (DID's), which describe the

[2] *Joseph J. Halpin and John P. Swirczynski, Nuclear Weapons Effects on Army Tactical Systems, Vol. II, Management, Harry Diamond Laboratories HDL-TR-1882-2 (May 1979).*

survivability data and plans that the contractor should furnish the Government and the times that they should be supplied. Volume II also lists[2] source selection evaluation criteria for bid evaluators to judge the adequacy of the bidders' responses to nuclear survivability. It also includes a statement on NWE testing that could be used in the CTP, a suggested form of solicitation instructions, and a work statement that could be used in the Request for Quotes (RFQ) or Request for Proposals to support nuclear survivability.

In addition to these, an Army regulation[3] provides regulatory support for nuclear survivability. The goals of AR 70-60 are to ensure the selection of the most appropriate nuclear survivability criteria for each critical system, to control the granting of waivers of nuclear survivability requirements, and to ensure that system survivability programs meet the imposed requirements. This regulation requires that specific nuclear survivability criteria be defined during the concept phase and that the Outline Development Plan and the contract documentation (such as the RFQ) include appropriate consideration of nuclear survivability. This early application of criteria should minimize the cost associated with hardening a system since the system is not designed and its documentation is not yet developed in the acquisition process.

4. SUMMARY

The tactical nuclear weapon environment threatens unhardened equipment, but a practical and cost-effective technology exists to develop survivable systems. The association of nuclear survivability with massive, lead-lined structures is antiquated. In fact, as a hardening technique, shielding is practical only against the EMP or thermal environment. (Shields against these environments are not high-density or massive structures.) Moreover, the search continues for better techniques to make the design of survivable equipment even cheaper, more effective, and more compatible with a system's required functional and physical characteristics and compatible with emerging materials and device technologies.

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[2] *Joseph J. Halpin and John P. Swirczynski, Nuclear Weapons Effects on Army Tactical Systems, Vol. II, Management, Harry Diamond Laboratories HDL-TR-1882-2 (May 1979).*

[3] *Army Nuclear Survivability, Department of the Army AR 70-60 (20 September 1977).*

Support exists for the system developer in the form of regulations, documentation, and nuclear expertise. However, the cost and risk factors for the development of survivable equipment depend on the developer's dedication and early attention to the nuclear survivability issues. Ample use of nuclear experts coupled with timely planning, designs, and documentation are the critical management factors.

Hardening options and operational fixes should be part of the system trade-off studies. Quite often, these studies reveal acceptable alternative ways of reaching required survivability levels and must be completed before any consideration is given to reducing or eliminating the survivability criteria.

On the technical side, the developer must be aware that the effect of nuclear weapons is not always obvious. A careful analysis and testing program that is guided or implemented by nuclear experts can significantly reduce the program risk and increase the compatibility with the system's required functional and physical characteristics. The system should be analyzed for its operationally critical areas with the nuclear survivability efforts being focused on these areas. In addition, the nuclear survivability program must consider the system as consisting of all the essential GFE in addition to the CFE.

Analysis is a necessary ingredient in a survivability program. Analysis is useful for pinpointing problem areas in systems and, if properly validated, can be used to minimize or eliminate tests of complete systems. Analysis and scale-model testing are used to determine worst-case configurations and orientations. However, the most important reason for using analytical techniques is that no nuclear effects simulator by itself duplicates all the important features of the threat environment. Moreover, test methods by themselves are not cost effective in accounting for the variations in system response that may be caused by variations among parts and materials or changes in production techniques, for example. For this reason, the best approach to system nuclear hardening validation is a proper mix of simulator test and analysis. These are balanced by comparing the results of the analysis to the results of tests in simulated environments. Once confirmed, this analysis technique can be used to predict the system response to the threat environment.

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